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Madrid as seen from Sentinel-1: preliminary results

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Abstract

This work presents an overview of Madrid from Sentinel-1A SAR sensor. For this purpose, a preliminary analysis was carried out involving 35 Interferometric Wide Swath SLC images from 29/10/2014 until 15/05/2016. SARPROZ software based on PSInSAR methodology was used. Results include geographic location of each PS, absolute and relative height (m), line-of-sight (LOS) velocity (mm/year), cumulative displacement (mm), standard deviation (mm), temporal coherence and displacement time series (mm) with respect to the acquisition date and linear model assumption. A spatial analysis was performed in order to evaluate PS density and quality over different Corine land use classes. Validation analyses were conducted using available permanent GNSS stations in the studied area. Visual insights into the deformation map allowed for the identification of clusters of PSs with similar subsiding or uplifting tendency. These cases were analyzed and connected to urban changes in the studied period. Results show that SARPROZ-processed Sentinel-1A images can provide a high number of reliable PS points in large cities as Madrid, allowing an almost continuous monitoring of ground and structures in this complex urban landscape.

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Keywords: PSInSAR; subsidence; urban; change detection

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1. Introduction

Sentinel-1A provides C-band radar images of the Earth at a 12-day revisit period since April 2014. Sentinel-1 products are optimized for DInSAR and InSAR, providing an almost continuous record of images for monitoring surface and structure deformations. The launch of Sentinel-1B on 25 April 2016 orbiting 180º apart from Sentinel-1A will provide an increased number of images, with 6-day revisit time.

Madrid presents a central urban area and growing surroundings, merging with other existing cities in the region. During last decade, important works such as the tunneling of railroad tracks and roads and metro's expansion and maintaining works, mainly focused in improving the transport network, have changed Madrid's shape. It is of special interest the M-30 Street case, undergrounded with twin tunnels, in the framework of the "Madrid Rio Park" project. This huge project recovered an area of 1,210,881 m^2 into a linear park (Madrid Council, 2016)[1]. Furthermore, the construction of urban underground metro and new railway infrastructures is leading to a more sustainable urban transportation, compatible with the conservation of green areas in the city. Sillerico et al. (2015)[2] applied Persistent Scatters Interferometry technique to estimate subsidence and displacement time series from ENVISAT Synthetic Aperture Radar images, acquired during M-30 tunneling between August 2003 and April 2008.

Madrid city feeds water from the Tertiary detritic aquifer (TDAM), a large tectonic depression (6,000 km^2) filled with continental deposits of Tertiary age. The city's population reached 3.2 million inhabitants in 2011, expecting an additional 10% in the next decade. Natural water supply of the city is provided by reservoirs and TDAM wells. The combination of drought periods and the rapid population growth (Martinez-Santos et al., 2010)[3] is responsible for the exploitation of groundwater. Ezquerro et al. (2015)[4] analyzed ground deformation related to TDAM extraction periods. Displacements and piezometric time series showed a correlation coefficient greater than 85% for all the wells.

Therefore, the relationship between ground deformation and urban dynamic factors, such as underground water levels and underground works and its effects can be monitored using DInSAR. Previous studies highlighted limitations such as: heterogeneous spatial distribution of Persistent Scatterers (PS), the absence of PSs in work areas and thresholds for velocity detection and low temporal resolution. Nevertheless, these limitations of DInSAR applications for infrastructure monitoring have been alleviated by the enhanced sensors onboard the current satellites. Therefore, DInSAR can be considered as a complementary technique with an exceptional added value and temporal analysis capability. This work aims at assessing the potential of Sentinel-1A imagery to monitor large urban areas as the city of Madrid (Spain).

Nomenclature

SLC	Single Look Complex
SAR	Synthetic Aperture Radar
InSAR	Interferometric Synthetic Aperture Radar
PSInSAR	Persistent Scatterer Interferometric Synthetic Aperture Radar
PS	Persistent Scatterer
GNSS	Global Navigation Satellite Systems
DTM	Digital Terrain Model
APS	Atmospheric Phase Screen
LOS	Line-of –Sight
TDAM	Tertiary Detritic Aquifer of Madrid
TOPS	Terrain Observation with Progressive Scans

2. Methods

For this paper, 35 Interferometric Wide Swath SLC images from 29/10/2014 until 15/05/2016 were downloaded from Sentinel Data Hub. Images were processed with SARPROZ software based on PSInSAR methodology. More details over acquisition parameters of the dataset under study are reported in Figure 1. Each image is connected with the Master image, chosen at the centroid of the distribution of perpendicular and temporal baselines, assessing also the weather conditions and precipitation information during Master acquisition time, in order to form an interferometric configuration for the analysis. A classical PSInSAR[5] methodology with the linear model assumption for the deformation time series was performed, resulting in 185,540 PS points with the temporal coherence higher than 0.7 over urban and rural area of 1,517 km^2 (122 PS/km^2).

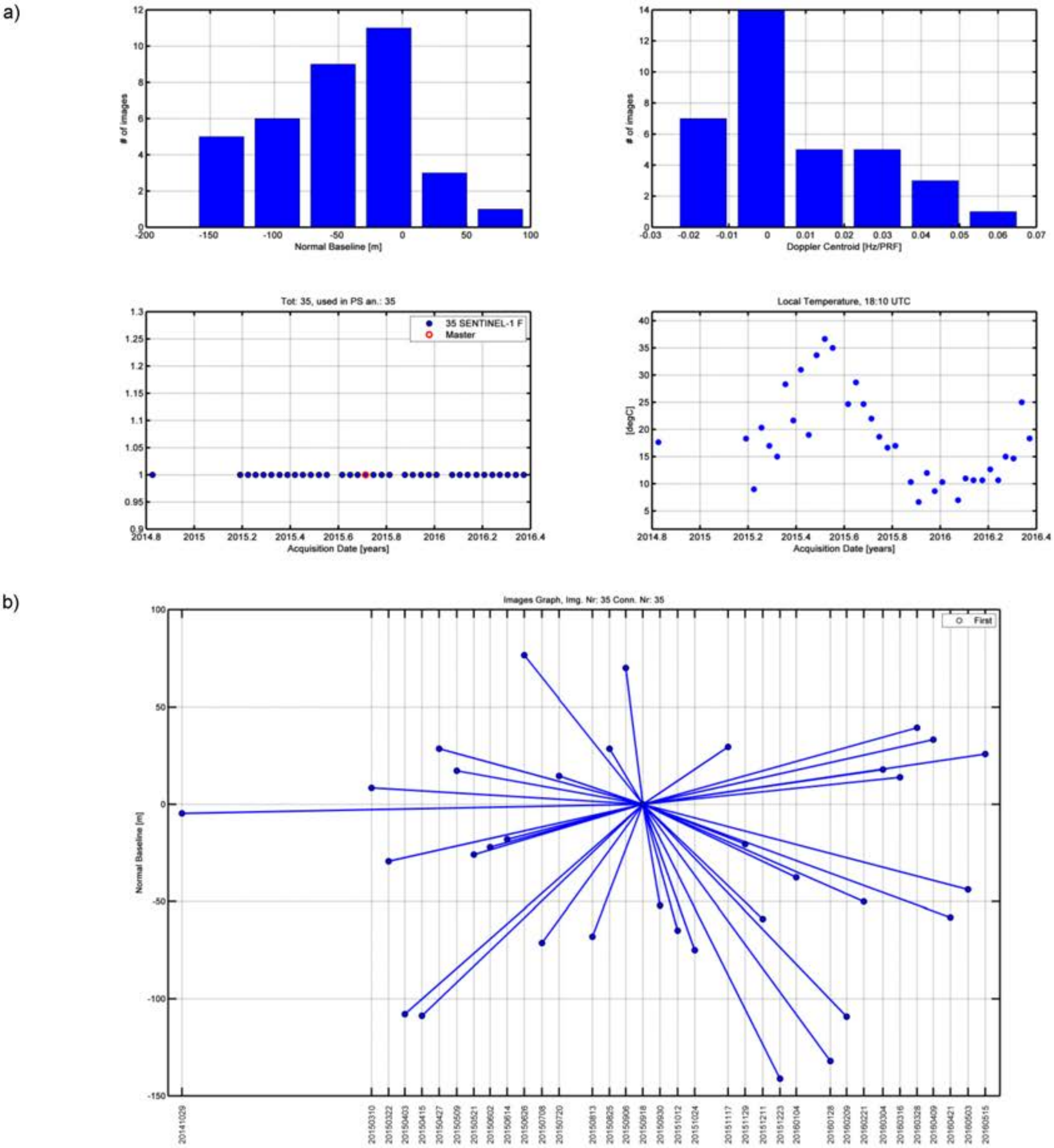

Fig. 1. Dataset statistics. In clockwise order, depicted are (a) the histogram of the perpendicular baselines, the histogram of the Doppler centroids, the temperature at the acquisition time and the time sampling of the images. (b) Interferometric configuration of the analysis: each image is connected to form an interferogram with the master image, chosen at the centroid of the distribution of perpendicular and temporal baselines.

These results were validated by TOPS processing on a subset of the whole area, focusing on refinement of the estimation parameters only for the problematic parts, where the deformation phenomena are present (Fig. 2). See

Section 3.2 for the details.

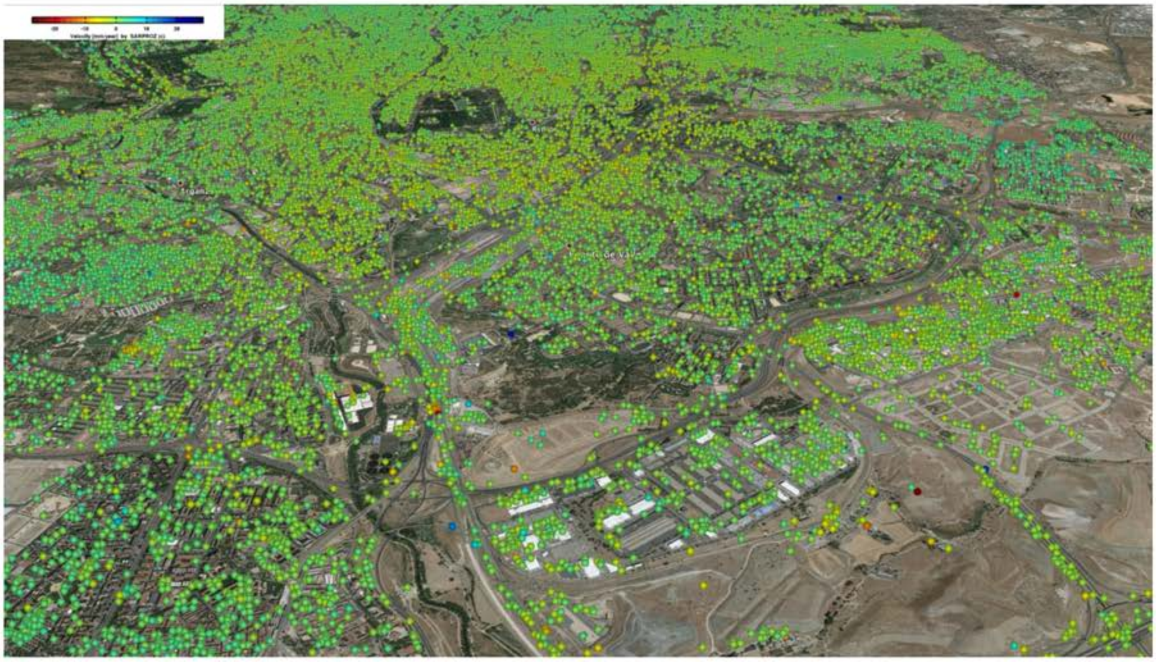

Fig. 2. Availability of PS points in the deformation map from the PSInSAR processing of Sentinel-1A over urban area of Madrid.

3. Results and Discussion

3.1. PS density and quality

Persistent Scatterers (PS) density and quality were analyzed over different Corine land use classes. Figure 3 presents the comparison between the area (%) and PS percentage (%) for main Corine Label 1 classes (Fig. 3a). It can be noted that artificial surfaces host over 90% of available PSs while accounting for less than 50% of the total surface. On the other hand, agricultural and forest areas show less available PS than artificial surfaces (Fig. 3a).

These results are confirmed by the analysis of PS densities for Corine Label 2 classes (Fig. 3b). Higher PS densities, over 3 points/ha, were obtained for urban fabric areas, including continuous and discontinuous urban fabric areas (Corine Label 3). On the opposite side, forests, agricultural areas green & sports urban areas, presented PS densities below 1 point/ha.

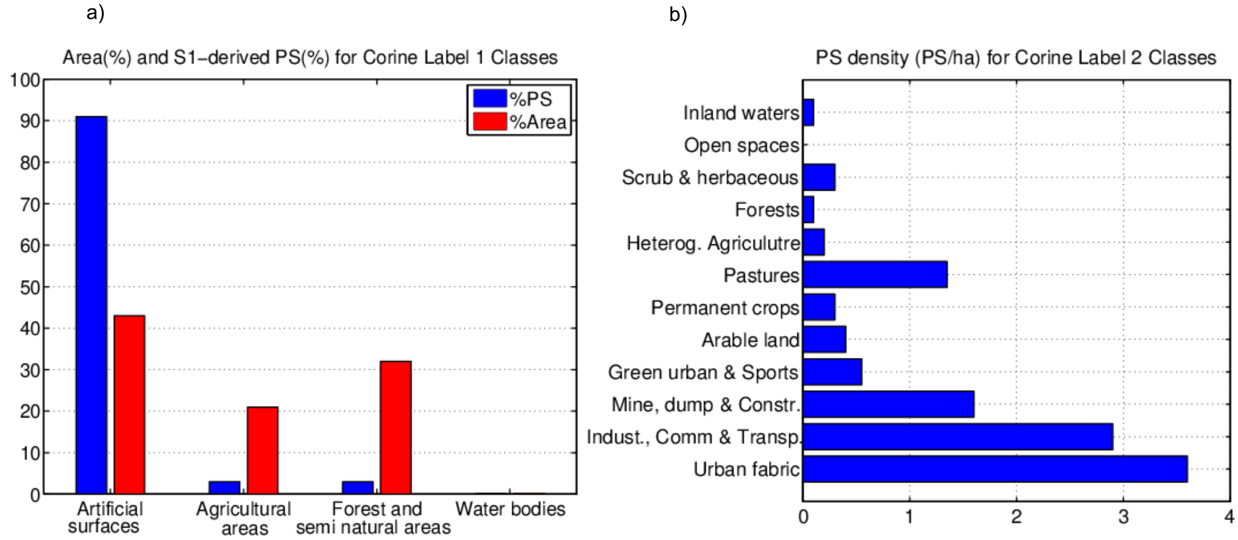

Fig. 3. Analysis of the areas and PS densities for (a) Corine Label 1 and, (b) Corine Label 2 classes in Madrid area (Spain).

3.2. Validation

For the validation, displacements series for VILL, 3CAN, IGNE and MER2 stations were calculated with reference to the initial date (29/10/2014) based on position series published by Nevada Geodetic Lab (2016)[6]. GNSS vertical diplacements for the monitoring period were related to vertical diplacements calculated with Sentinel-1A imagery, as presented in Figure 4. Line-of-sight (LOS) displacements were recomputed to vertical displacements by dividing them by the cosine of the incidence angle (39.203 deg).

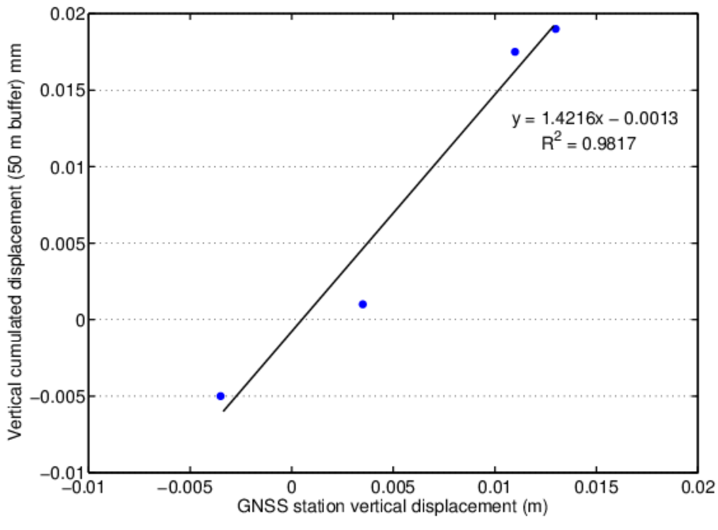

Fig. 4. Sentinel-1A vertical displacements for a 50-m buffer around selected GNSS stations in Madrid area (Spain).

3.2. Man-made structures and detected deformation processes

Visual insights into the deformation map were applied to detect urban changes in the studied period selecting moving points with temporal coherence higher than 0.7. As a result of this preliminary analysis some areas were identified, mostly related to construction works (River Manzanares banks, new urbanization areas, new structure, etc.) and some other to ground-structure interaction processes as the subsidence of a railway viaduct and buildings under construction in a leisure park (Figs.5 & 6).

As an example, Santa Catalina railway viaduct case is presented in Figure 5. The viaduct was doubled in 2002 in order to allow railway transport over existing train tracks. In addition, other works have been carried out in the surroundings for the viaducts for High-speed train lines. During the studied period a subsidence trend was detected in the 2002-constructed viaduct with a cumulated displacement over of 30 mm and velocities between 20-25 mm/year.

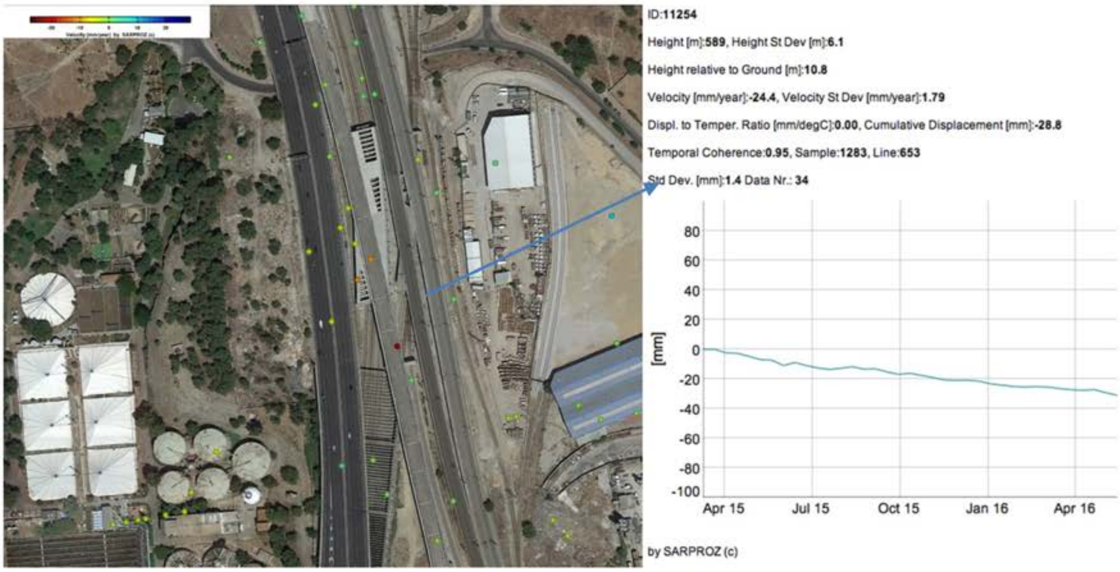

Fig. 5. Detection of changes in Santa Catalina railway viaduct. Madrid area (Spain). . Displacement time series in (mm) from surroundings of affected area on the right.

Deformation signal was also detected for other areas in urban Madrid, some of them related to built structures while others were located in pavements and parks (Fig. 6). Detected signals were contrasted with other sources, such as reports of public works in Madrid and the multitemporal analysis of aerial photographs. Some signals were discarded after this analysis, corresponding to ongoing works or the building of structures.

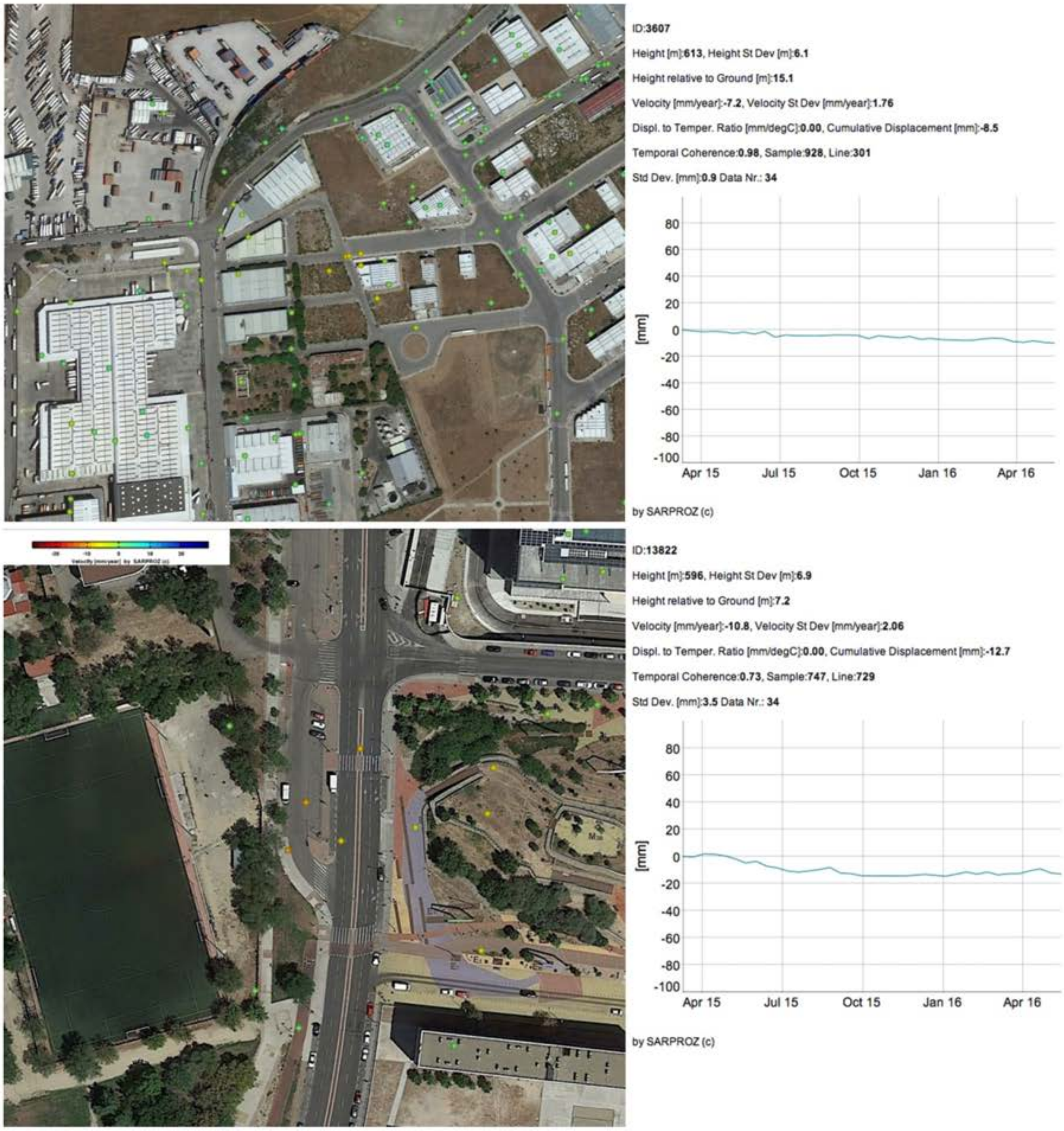

Fig. 6. Deformation signal detected in urban areas. Displacement time series in (mm) from surroundings of affected areas on the right.

4. Conclusions and future work

Sentinel-1 imagery can provide a significant number of Persistent Scatterers for deformation monitoring of urban areas such as Madrid. A preliminary analysis identifies higher densities of PSs on artificial surfaces, especially urban fabric (over 3 PS/ha) as well as industrial, commercial and transport areas. On the other hand, forests, agricultural areas green & sports urban areas, presented PS densities below 1 point/ha. It is recommended to compare Sentinel-1 PS characteristics with previous ESA SAR sensors (Envisat and ERS) over the same area.

Sentinel-1A allowed for identification of critical areas in Madrid area, mostly related to the construction works (River Manzanares banks, new urbanization areas, new structures, etc.) and some other ground-structure interaction processes as the subsidence of a railway viaduct and buildings under constructions structures in a leisure park.

Further work will imply combining ascending and descending geometries and improving SAR processing with more detailed DTMs, better co-registration strategies, enhanced Atmospheric Phase Screen (APS) estimation, using different models for the extraction of the deformation signal (non-linear, seasonal) and applying Quasi-PSInSAR[7] analysis in order to obtain information from partially coherent targets and increase the density of PS points over rural areas. Data mining algorithms for outlier detection, as proposed in Bakon et al. (2016)[8] will be tested in urban areas to enhance the PS selection.

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